AFML-TR-68-251

SOME PROPERTIES OF IRON, COPPER, AND SELECTED ALUMINUM ALLOYS INCLUDING TRUE STRESS-TRUE STRAIN AT REDUCED TEMPERATURES

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FOREWORD

Some of the individual tasks covered in this report were carried out by AFML personnel while the remainder was pursued by the University of Dayton Research Institute, Dayton, Ohio, initiated under Air Force Contract F33615-67-C-1087, and completed under F33615-68-C-1138, Project 7360, "Chemistry and Physics of Materials", Task 736006, "Hypervelocity Impact Studies". The work was administered by the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio with Mr. Alan K. Hopkins (MAYH) as Project Engineer.

The authors gratefully acknowledge the assistance of Mr. H. F. Swift for his helpful discussion, Mr. P. Graf for his aid in having the oscillographic test records read, and Mr. K. Story for his timely production of liquid helium.

This report was submitted by the authors in August 1968. The University of Dayton report number is UDRI-TR-68-38.

This technical report has been reviewed and is approved.

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ABSTRACT

The metallurgical and mechanical properties of several face centered cubic materials (1100 Al, 7075-0 Al, 7075-T6 Al, OFHC Cu) and a body centered cubic material (Armco iron) were examined. Prior to undergoing tensile testing the materials were insured to have a nonoriented equiaxed grain structure and underwent chemical analysis and hardness tests. The materials were then tensile tested at 296°K in the atmosphere, at 77°K in a liquid nitrogen bath, and at 4°K in liquid helium. A continuous record of the axial load and of two perpendicular specimen profile traces produced a measurement of specimen true stress-true strain. Engineering stress-strain, elongation, and reduction in area were also calculated.

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I. INTRODUCTION

The investigation of the response of materials to hypervelocity impact, being conducted by the Air Force Materials Laboratory (AFML) light-gas gun facility, deals with several types of materials impacted under various conditions. A concurrent program of materials characterization was initiated for two basic reasons. First, it was necessary to make certain that the materials under study were homogeneous and possessed both uniform and well known properties. In those cases where a material was found to be nonhomogeneous steps were taken to make it uniform. Secondly, since material properties play an important role in impact effects, such as cratering in a semi-infinite target or hole production in a thin plate impact, it was necessary to measure various mechanical properties before these relationships could be established.

This materials characterization is broken into the following general categories: chemical analysis, metallurgical analysis, and mechanical properties including hardness and true stress-true strain tensile relationships. The tensile tests in this phase of the program were conducted at three temperatures (296°K, 77°K, 4°K) and involved five materials (1100 Al, 7075-0 Al, 7075-T6 Al, OFHC Cu, Armco iron). All the materials tested were of the same stock as that used in the AFML hypervelocity impact studies. This report is a listing of the results of this materials characterization and should be considered with two previous reports (Reference 1 and 2) which outlined the project and presented initial data. In some cases data from these reports is repeated here for completeness.

II. BACKGROUND

The effect of low temperatures upon various materials is surveyed in Reference 3. Briefly, materials with a body centered cubic structure (Armco iron) may be expected to become brittle at low temperatures. As the ductility approaches zero fracture naturally occurs suddenly and without warning. Materials with a face centered

cubic structure (OFHC Cu, 1100 Al, 7075-0 Al, 7075-T6 Al) may be expected to retain their ductility at low temperatures and show an increase in tensile strength. As a material is alloyed however, these basic trends may be modified to account for the influence of the alloying additions.

III. TEST MATERIALS

The materials selected for this particular study were subjected to the following series of operations to determine their chemical and structural properties:

1. Heat treatment (manufacturers).
2. Metallographic examination (to insure nonoriented equiaxed grain structure).
3. Upset forging and further heat treatment (if oriented grain structure was initially present).
4. Additional metallographic examination (to check results of upset forging and for grain size determination).
5. Chemical analysis.
6. Hardness measurements.

1100-0 Aluminum

The material was taken from a die cast ingot with original dimensions of 16-1/2 inch diameter x 24 inch length. The ingot was in an as cast condition and metallographic examination revealed a nonoriented equiaxed grain structure.

7075-0 Aluminum

The material was taken from die cast ingots with original dimensions of 3-1/2 inch diameter x 24 inch length. The ingots were annealed in air for two hours at 775°F and air cooled. Metallographic examination indicated the grain structure to be nonoriented equiaxed.

7075-T6 Aluminum

The material was taken from die cast ingots with original dimensions of 3-1/2 inch diameter x 24 inch length. The ingots were solution heat-treated in air for eight hours at 870°F and quenched in water at 150°F. At the conclusion of aging for 26 hours at 250°F, metallographic examination showed a nonoriented equiaxed grain structure.

OFHC Copper

The material which was taken from ingots, formed by an electrolytic process, with original dimensions of 4 inch diameter x 36 inch length, was found to have some grain orientation. The ingots were cut into sections 6 inches long and each section was upset forged at 1425°F along its three principle axes to final dimensions of 3-1/4 inch x 3-1/4 inch x 7-1/4 inch length and then air cooled. After vacuum annealing for 3-1/2 hours at 300°F and furnace cooling, additional metallographic examination revealed the presence of a nonoriented equiaxed grain structure as a result of the forging operations.

Armco Iron

The material, taken from very highly refined, as cast ingots with original dimensions of 4 inch diameter x 36 inch length, was found to have some grain orientation after initial metallographic examination. The ingots were cut into sections of 12 inch length. Each section was upset forged along its three principle axes to final dimensions of 5-1/2 inch diameter x 6-1/2 inch length then air cooled. After normalization the sections were air cooled and shot blasted. Additional metallographic examination revealed that a nonoriented equiaxed grain structure had been achieved as a result of the forging operations.

Table I (page 4-5) lists for each material:

1. Chemical analysis (parts per million).

2. Hardness measurements taken over a cross sectional area (Brinell Hardness Number; 500 kg load applied for 30 sec; 10 mm dia. ball).

3. Grain size (ASTM Number).

4. Average grain diameter (mm).

TABLE I

TEST MATERIALS METALLURGICAL DATA

Elements	1100-0 Aluminum			7075-0 Aluminum	
	Chemical Analysis (PPM)	Chemical Analysis (PPM)	Manufacturing Limits (PPM)	Chemical Analysis (PPM)	Manufacturing Limits (PPM)
Be				30	
C					
O_2					
Mg	10	10		23800	21000-29000
Al					
Si	1900	1100	10000	1600	5000
P					
S					
Ca					
Ti	200	40		300	2000
V					
Cr	10	20		2000	1800-4000
Mn	50	60	500	70	3000
Fe	4100	4800	10000	1500	7000
Co					
Ni					
Cu	1000	800	2000	16000	12000-20000
Zn	200	50	<900	53300	51000-61000
Zr					
Mo					
Ag					
Cd					
Sn					
Sb					
W					
Pb					
Bi					
Ce					
BHN (500 kg load, 30 sec, 10 mm dia. ball)	23.5-25.5			58.0-59.5	
Grain Size (ASTM No.)	0			3.5	
Avg. grain dia. (mm)	0.0500			0.0149	

Elements	7075-T6 Aluminum		Armco Iron		OFHC Copper
	Chemical Analysis (PPM)	Manufacturing Limits (PPM)	Chemical Analysis (PPM)	Chemical Analysis (PPM)	Chemical Analysis (PPM)
Be	30				
C				170	8.5
O_2					1.3
Mg	23300	21000-29000	<10		
Al			<10		< 5
Si	1400	5000	140	40	1
P				40	
S				200	
Ca			<10		
Ti	400	2000	<10		
V			<10		
Cr	2000	1800-4000			
Mn	60	3000	140	400	<1
Fe	1500	7000	Mfg. Limits	99.9%	<10
Co			<10		
Ni			140		1
Cu	15700	12000-20000	140	1120	Mfg. Limits 99.99% Cu
Zn	54000	51000-61000			<10
Zr			<10		
Mo			140		
Ag					<10
Cd					<10
Sn			10	50	2
Sb					<10
W			<1000		
Pb			<10		3
Bi					< 5
Ce			140		
BHN (500 kg load 30 sec, 10 mm dia. ball)		150.0-159.0	70.0-72.0		48.5-50.5
Grain Size (ASTM No.)		3.5	2.5		4.5
Avg. grain dia. (mm)		0.0149	0.0211		0.0106

Photomicrographs of each material, showing grain structure, are included in Appendix I.

Blanks of each material with original dimensions of approximately 1/2 inch x 1/2 inch x 2-1/2 inch length were cut in both the longitudinal and transverse directions from each ingot. The tensile specimens were machined in accordance with the dimensioned drawing (Figure 1).

IV. MECHANICAL PROPERTIES

All materials used in this study underwent tensile tests on equipment designed to produce a record of true stress-true strain and operate at reduced temperatures. The design and capabilities of this equipment are discussed in Reference 4. Briefly, the tests were conducted at room temperature in the atmosphere, at 77°K in a liquid nitrogen bath using one cryostat, and at 4°K in liquid helium using a second cryostat. The first cryostat is capable of operation at a number of specific temperatures as low as 77°K; the second cryostat is capable of operation from 4° to 77°K.

A diameter sensing gage which constantly traversed the specimen produced a continuous record of the specimen profile. This measure coupled with a continuous record of the axial load allowed the computation of true stress and true strain which is a more meaningful measure of a materials mechanical and metallurgical characteristics than the conventional engineering stress-strain relationship. The engineering relationship was also computed on the basis of the load record and the crosshead motion. All tests were conducted at an initial strain rate of .01 in/in/min. Since the crosshead speed was constant this strain rate decreased as the specimen elongated. Upon the formation of a neck in the specimen (nonuniform plastic deformation) the strain rate increased drastically.

The true stress of a specimen was found within ±2 to 4% (Reference 4). This figure represents a combination of the errors in measuring the load and the specimen diameter and is based upon the standard deviations of the load and diameter calibrations from least squares lines.

The severe necking encountered with the OFHC copper specimens exceeded the range of the diameter gage. At 296°K and 77°K the range was approximately .250 to .100 inch. At 4°K, due to a restriction caused by the bellows of the tensile dewar, the range limits were approximately 0.250 to 0.160 inch. Only the copper specimens were limited by these ranges. Calculations for the copper specimens

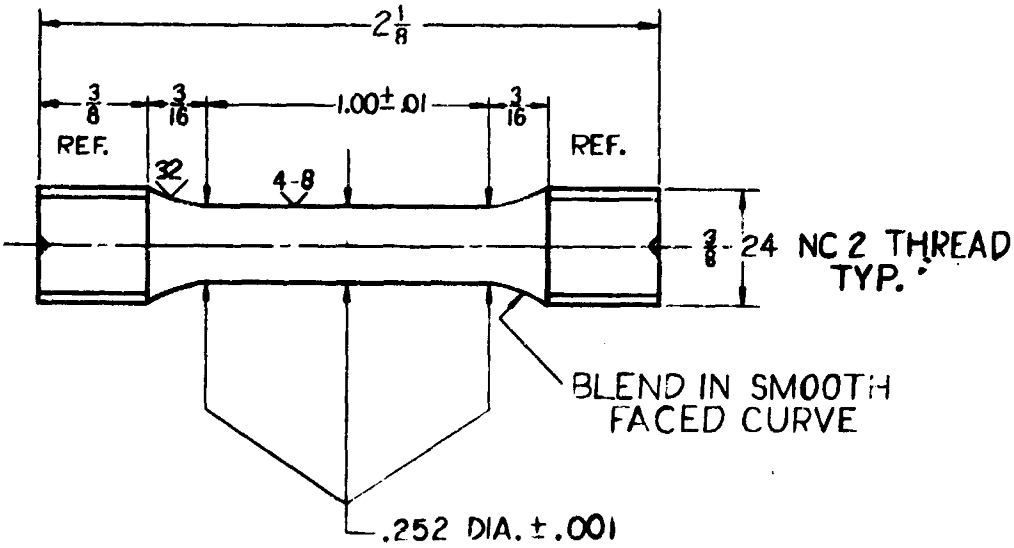

Figure 1. Threaded True Stress-True Strain Tensile Specimen

involving the use of the final diameter are based on post fracture measurements. The true stress-true strain curves for copper are extrapolated to this post fracture measurement.

The tensile data presented in Table II is a summary obtained from all the tests conducted. All available data, including tests not producing true stress-strain records, is given to demonstrate the uniformity of the data. The data marked by the asterisk was contained in the preliminary report (Reference 2) and represents tests conducted at the Army Materials Research Agency, Watertown Arsenal by John Nunes at a similar test speed using material from the same stock. In addition to the specimen orientation with respect to the billet from which it was cut and the test temperature the following information is given for the consecutively numbered tests of each material:

1. Percent Elongation was primarily determined by measuring the total crosshead motion and then correcting this measure for the elongation of the specimen grips and pull rods, thus resulting in the deformation of the tensile specimen. Post fracture measurements of the gage and total specimen lengths provided a check of the percent elongation measured by the primary means. In all cases Table II gives the result of the crosshead measure, except

TABLE II

TENSILE TEST DATA SUMMARY

Material	Test No.	Specimen Orient.	Temperature °K	% Elongation	% Area Reduction	Tensile Strength	True Fracture Stress	True Fracture Strain	Energy/Unit Vol. to Fracture
1100 Al	1	Long	297.8	34.0[1]	66.4[2]	12.93	-	-	-
	2	Tran	296.8	29.2	63.2	13.06	27.3	1.008	20.38
	3	Long	296.6	31.4	64.4	12.87	26.8	1.03	21.01
	*	Tran	193	-	70	15.14	31.97	1.160	27.58
	*	Long	193	-	65	14.94	30.12	1.100	24.58
	4	Tran	77	50.0	56.8	25.72	53.9	.843	31.87
	5	Long	77	42.2	54.7	26.81	53.4	.788	30.30
	6	Long	4	42.9[1]	34.5	48.35	72.6	.424	22.51
	7	Long	4	41.0	34.0	47.47	69.7	.412	19.27
7075-0 Al	1	Long	298.3	18.0	36.5[2]	32.60	44.6	.414	-
	2	Long	298.4	18.9	33.2	32.76	47.5	.420	16.13
	3	Tran	296.4	18.7	35.7	34.26	50.6	.445	18.14
	*	Tran	193	-	38	35.89	52.25	.472	20.32
	*	Long	193	-	38	34.78	50.45	.462	19.26
	4	Long	77	24.6	23.3	46.74	60.7	.267	13.28
	5	Tran	77	19.6	21.0	49.69	63.3	.24	12.13
	7	Long	4	19.4	16.8	66.19	79.2	.190	11.54
	8	Long	4	16.4	14.9	64.52	76.03	.175	9.06
7075-T6 Al	1	Long	300.7	16.5	20.2[2]	79.72	-	-	-
	2	Long	297.2	13.5	20.4	79.69	97.0	.232	19.85
	3	Tran	296.7	12.2	19.5	78.99	97.2	.231	19.94
	*	Tran	193	-	14	85.30	96.33	.123	10.36
	4	Long	77	3.8	4.0	91.34	94.0	.041	3.54
	5	Tran	77	2.8	2.8	91.10	92.5	.028	2.48
	6	Long	4	1.9[1]	2.8[2]	102.75	104.6[2]	.024[2]	2.48
	7	Long	4	2.6	1.6[2]	102.87	104.7	.022	2.24

OFHC Cu	1	Long	296.6	58.4[1]	88.1[2]	29.06	110.0	2.18	150.92
	2	Long	297.2	54.3	87.1[2]	29.04	96.3	2.09	133.24
	4	Long	77	68.4	86.7[2]	48.85	177.5	2.00	218.3
	5	Long	77	70.6	86.5[2]	47.42	184.0	2.00	224.6
	6	Tran	296.0	49.4	82.4[2]	29.80	95.2	1.73	107.68
	7	Tran	77	65.0	83.7[2]	47.43	157.2	1.82	184.96
	8	Long	4	82.4	82.7[2]	57.63	221.0	1.76	236.8
	9	Long	4	75.3	82.9[2]	59.03	221.0	1.77	241.2
Armco Iron	1	Long	299.2	38.8	72.1[2]	40.54	-	-	-
	2	Long	296.9	39.6	76.3[2]	39.41	-	-	-
	3	Long	297.0	36.2	66.8[2]	41.04	87.2	1.10	70.42
	4	Long	296.2	1.6	73.5[2]	40.09	89.95	1.328	88.54
	5	Tran	296.8	57.6	71.5[2]	40.20	91.6	1.255	84.95
	6	Long	77	1.0	.6	96.73	97.2	.005	.24
	7	Tran	77	0	1.3	93.86	95.13	.0134	.89
	8	Long	77	.6	.5	94.91	95.34	.005	.24
	9	Long	4	.2	0	92.36	92.36	0	0
	10	Long	4	.9	0	94.30	94.30	0	0

1. Based upon post test measurement of total specimen length.
2. Based upon post test diameter measurement.

where noted, in which case it was not available and the total length measure is presented. This secondary measure was found to be comparable, although often 1-2% higher than, the primary measure.

2. Percent Area Reduction was computed from both the final reading of the diameter gage and the post fracture diameter. The computation based on the final diameter gage reading is presented in the Table except for those noted cases where the specimen necking exceeded the range of the gage or the diameter gage reading was unavailable or unreliable.

3. Tensile Strength was computed using the maximum load seen by the specimen divided by its original cross sectional area at the temperature at which the test was conducted.

4. True Fracture Stress is the fracture load divided by the minimum cross sectional area at fracture. In those cases where the material was very ductile and no distinct fracture was evident the true fracture stress is the result of extrapolating the plastic deformation portion of the true stress-true strain curve to the true strain at fracture. A check of this extrapolation technique with materials showing a distinct fracture verified its accuracy.

5. True Strain is derived from the measure of the minimum specimen diameter, and is based on the definition of true strain $\varepsilon = \int_{Lo}^{Li} \frac{dL}{L} = \ln \frac{Li}{Lo}$ where an initial increment of length Lo has been plastically deformed to a length Li. This further reduces to $\varepsilon = 2 \ln \frac{Do}{Di}$ (where Do is the original diameter and Di is the instanteous diameter) since volume is conserved during plastic deformation.

6. Energy to Fracture Per Unit Volume was computed using a planimeter to measure the area under the true stress-true strain graph. In some cases the area was to the extrapolated true fracture stress points mentioned earlier.

Results

True stress-strain and engineering stress-strain graphs for each material are presented in Appendix II. The graphs starting on page 12 (Figures 2-6) depict the changes in tensile strength, percent elongation, percent area reduction, true fracture stress, and energy per unit volume

to fracture as a function of temperature for each material. The points in these graphs are averages of the values in Table II.

They show that although a general trend may exist that the change is not linear with respect to temperature. Rather, the graphs are non-linear and marked by plateaus and even reversals in direction. Even two similar materials such as 7075-0 and T6 Al do not show the same trends. Generally, however, a distinction can be made between the two different crystal structures tested.

Tensile Strength

The tensile strengths of the face centered cubic aluminums increased in a very similar manner as temperature decreased. The strength values maintained the same relation to each other at reduced temperatures as they do at room temperature. OFHC copper showed an approximately linear increase in tensile strength. The body centered Armco iron, however, increased in strength to about 77°K then remained essentially constant forming a plateau. This plateau seemed to be the mark of the severe embrittlement of the iron.

Percent Elongation

The softer aluminums (1100-0, 7075-0) behaved similarly as the temperature drops as they both showed an initial increase in elongation followed by a decrease. The softer 1100-0 Al did not drop below its room temperature level as the 7075-0 did, however. The hard 7075-T6 Al and the Armco iron behaved in a similar way as both showed a severe decrease in elongation the iron becoming almost totally brittle while the Al maintained a few percent elongation even at 4°K. The copper was not adversely affected by the decreased temperature and showed a general increase in elongation.

Percent Area Reduction

A trend similar to elongation is seen for area reduction in that the two softer aluminums and the 7075-T6 and Armco iron behave similarly. All four materials show a decrease in percent area reduction; the hard aluminum and iron showing the fastest decrease. The copper again is changed little by decreases in temperatures as the corresponding decrease in area reduction is only a couple of percent. Although the trends for elongation and reduction in area are similar, they are two distinct measures and should be considered as such.

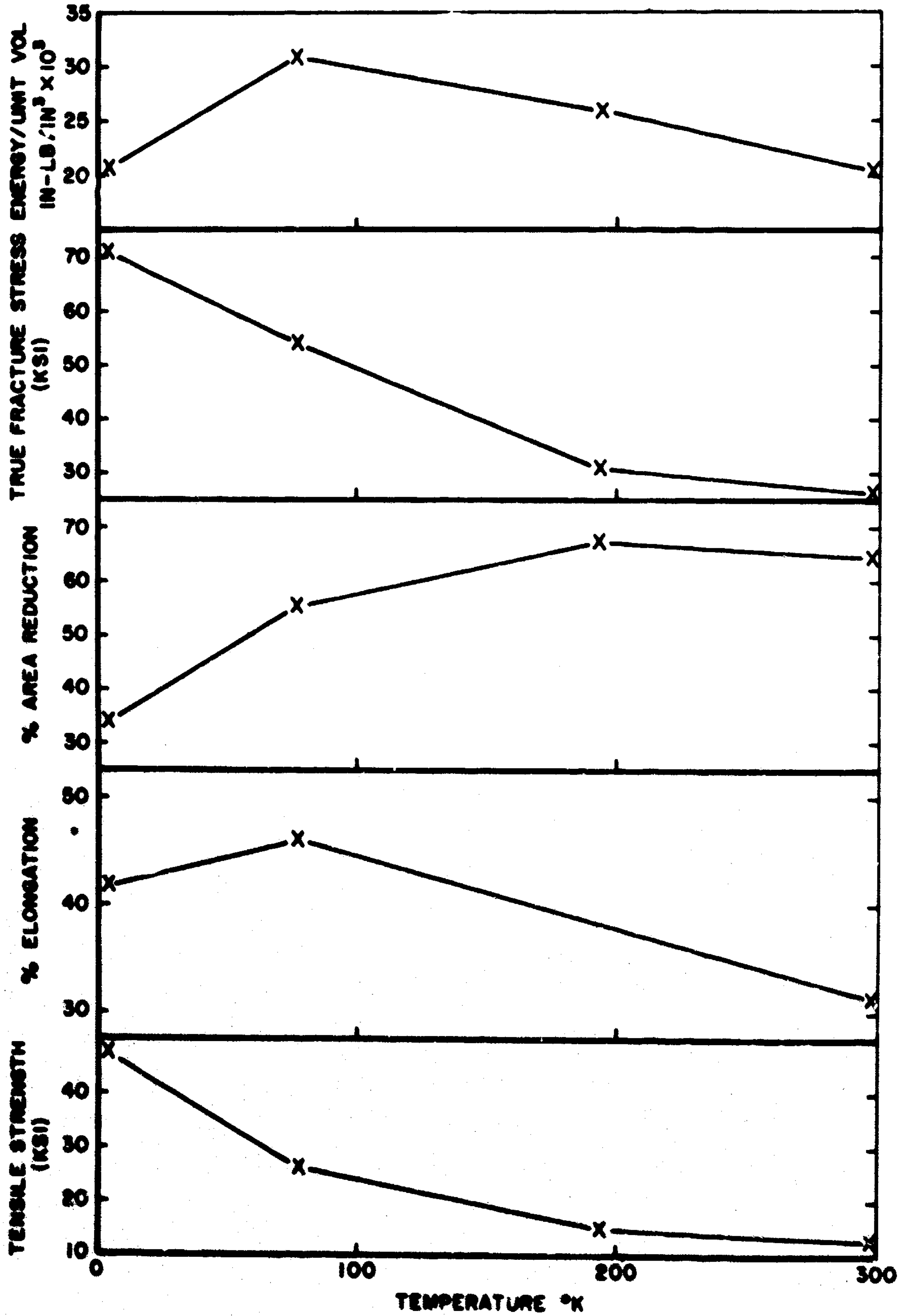

Figure 2. Tensile Properties of 1100-0 Al

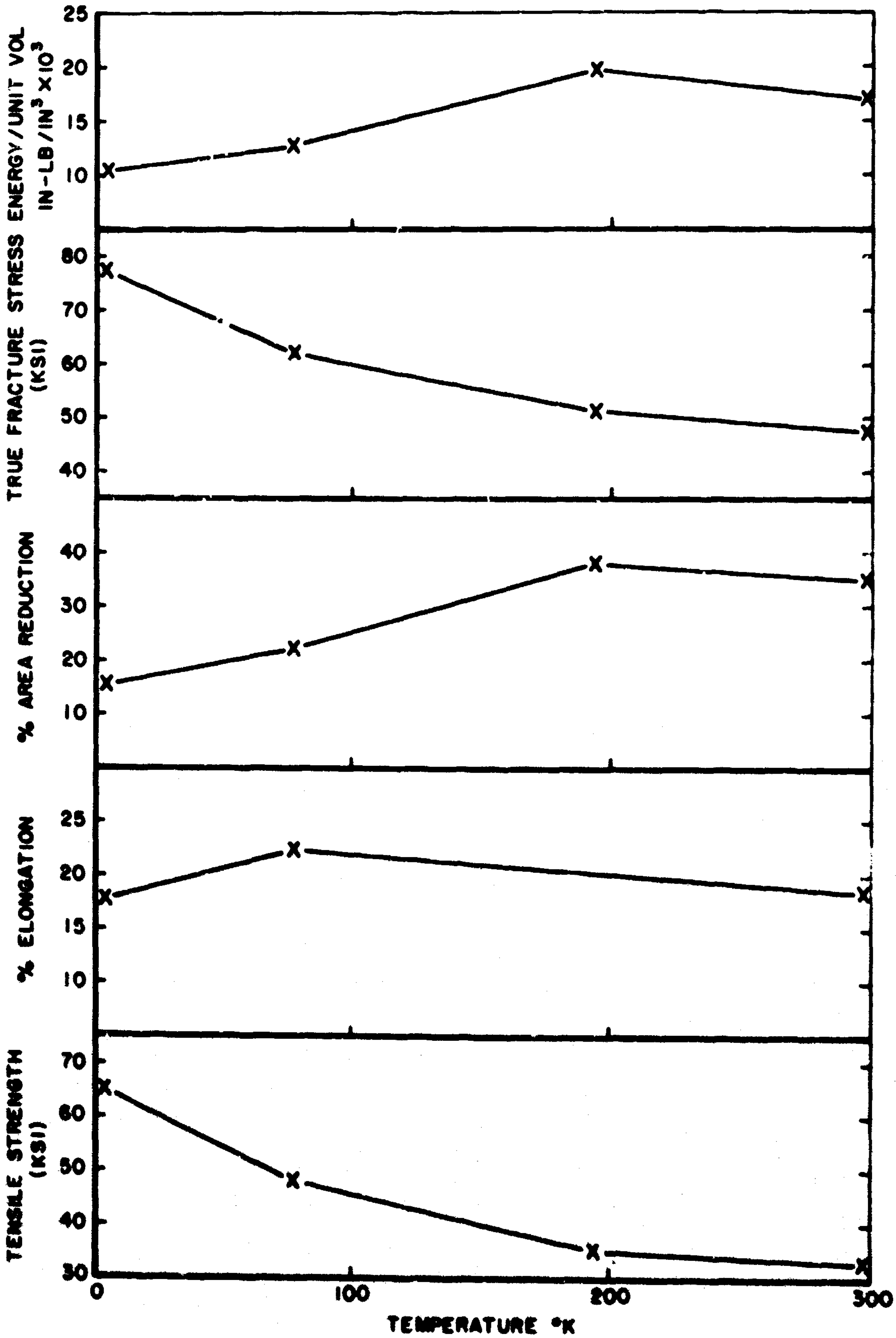

Figure 3. Tensile Properties of 7075-0 Al

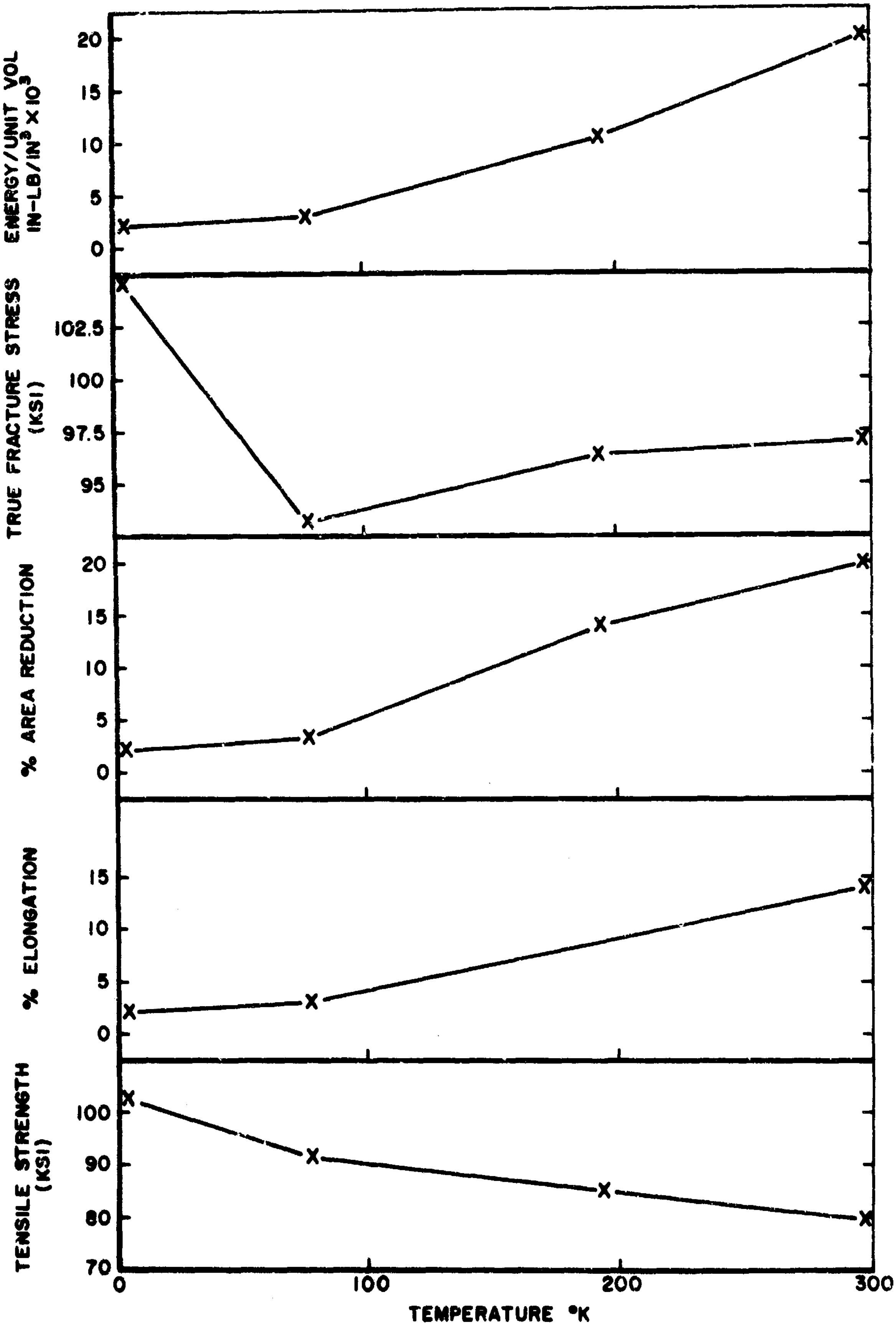

Figure 4. Tensile Properties of 7075-T6 Al

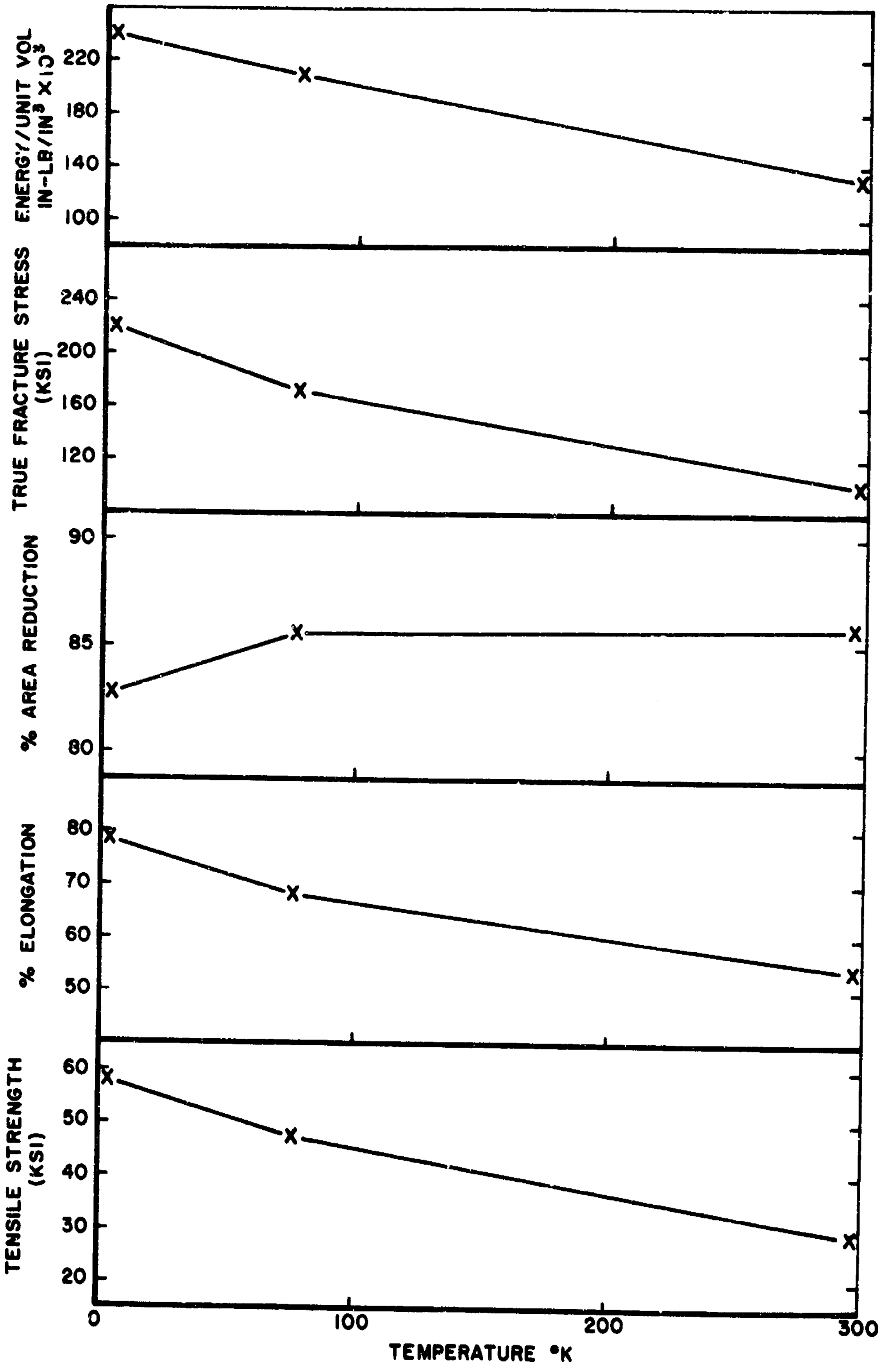

Figure 5. Tensile Properties of OFHC Cu

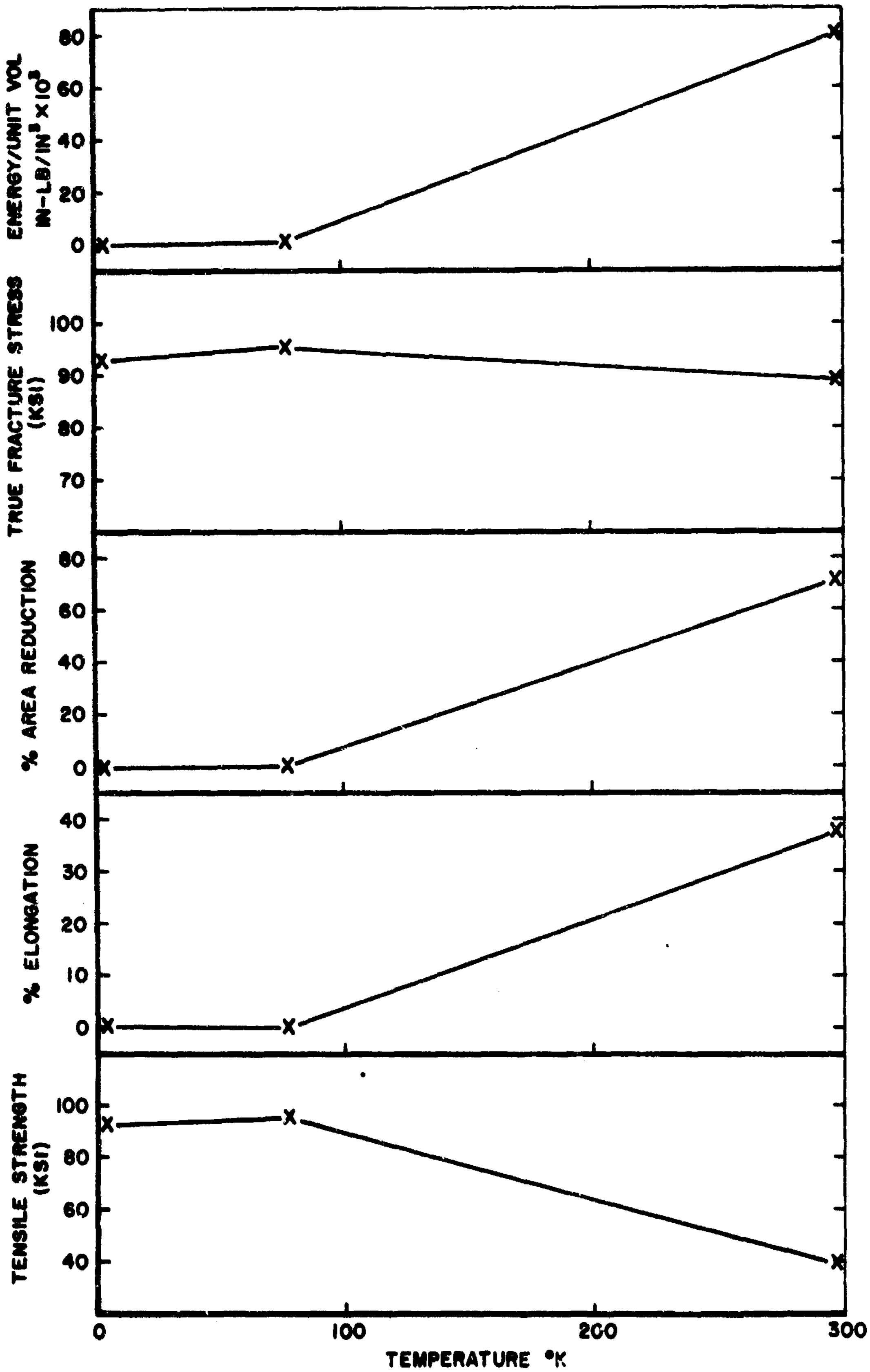

Figure 6. Tensile Properties of Armco Iron

In the elastic region the two measures may be related by Poisson's ratio and during uniform plastic deformation they may be related by realizing that volume is conserved, however, upon the formation of a neck these simple relationships no longer apply. Reference 5 contains a detailed study of this relationship.

True Fracture Stress

True fracture stress is a combination of the load supported at fracture and of the area reduction. When the extrapolated values are used for the true fracture stress, the voids which form in the area of a neck prior to fracture and thus reduce the effective area are being taken into account. Generally, a net increase in true fracture stress was seen, however, due to the relative effects of area and load the 1100 Al, 7075-0 Al, and OFHC Cu showed continuing increases while the 7075-T6 Al unexpectedly decreased to 77°K then increased greatly between 77°K and 4°K. The Armco iron remained relatively constant throughout the temperature range.

Energy Per Unit Volume to Fracture

The energy to fracture is a function of the true stress at fracture, the area reduction, and the slope of the elastic and plastic portions of the true stress-true strain relationship. The 1100 Al and 7075-0 Al were similar as they increased then decreased as the temperature was lowered. However, the decrease in the 1100 started much later than it did in the 7075-0 Al. The 7075-T6 Al and iron were again similar as both decreased to 77°K then remained constant to 4°K. The copper showed a linear increase to 4°K.

As a result of some of the trends noted above and particularly the great ductility of some of the materials at low temperatures a project is underway to determine the mode of failure and explain this ductility. Fractographs which are photographs of a carbon replica of the specimen's fracture surface as viewed under an electron microscope have been made of all the body centered cubic materials tested. Also, additional tensile tests are planned at each temperature with a small grained 1100 Aluminum.

Further, all of the materials mentioned in this report have been impacted in a semi-infinite form (thick block) on the AFML light-gas gun range at room temperature (297°K), in a dry ice-acetone bath (193°K), and in a liquid nitrogen bath (77°K). Further impacts are planned for each material in liquid helium (4°K).

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APPENDIX I

Each material underwent a metallographic examination to insure a nonoriented equiaxed grain structure. Material specimens representing the principal axes of the billet were mounted, polished and etched for examination. Photomicrographs of an etched surface of each material appear in this appendix.

Figure 7. Grain Structure of 1100-0 Al (100x)

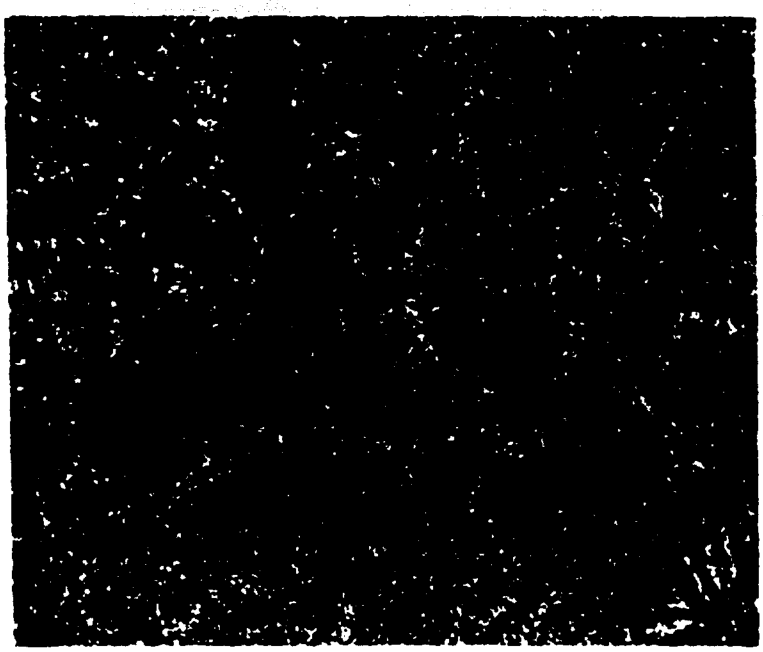

Figure 8. Grain Structure of 7075-0 Al (100x)

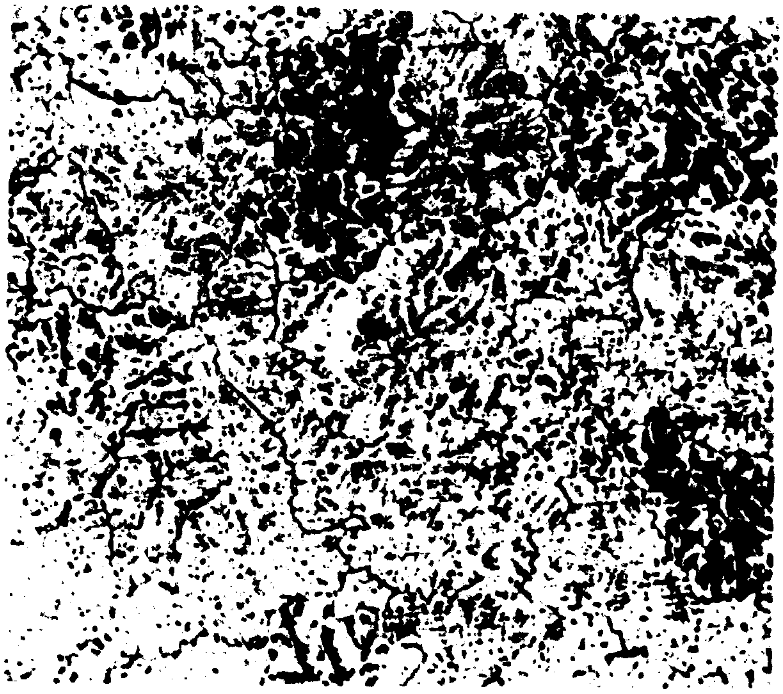

Figure 9. Grain Structure of 7075-T6 Al (100x)

Figure 10. Grain Structure of OFHC Cu (100x)

Figure 11. Grain Structure of Armco Iron (100x)

APPENDIX II

This appendix presents true stress-true strain and engineering stress-strain graphs for each material at all of the test temperatures. Data points are included on the graphs. The dotted lines show the points to which various tests were extrapolated. Serrated yielding occurred at $4^{\circ}K$ in some of the materials. This is shown on the engineering stress-strain graphs while the true stress-true strain graphs trace the upper load limit of these serrations.

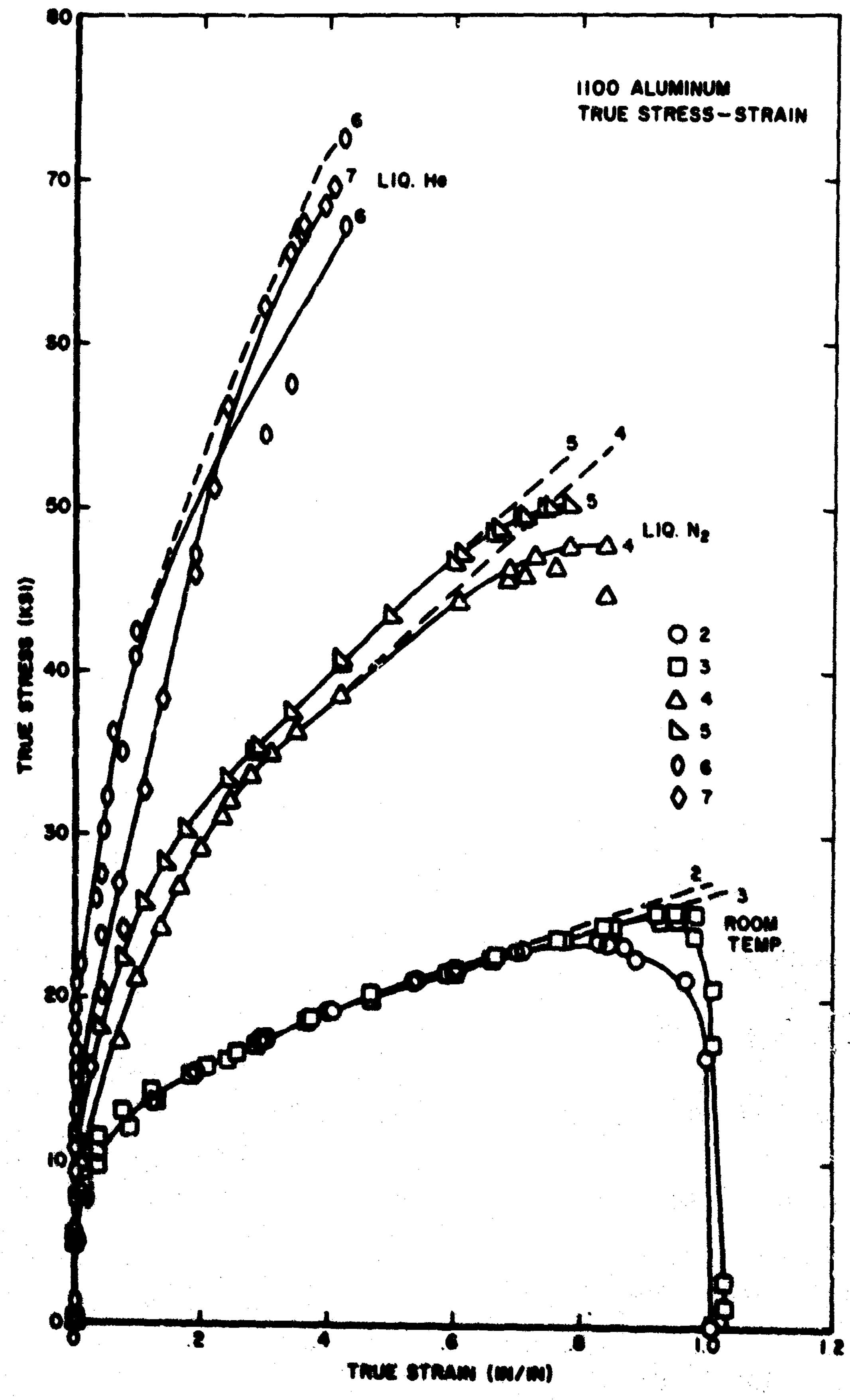

Figure 12. True Stress-Strain 1100-0 Al

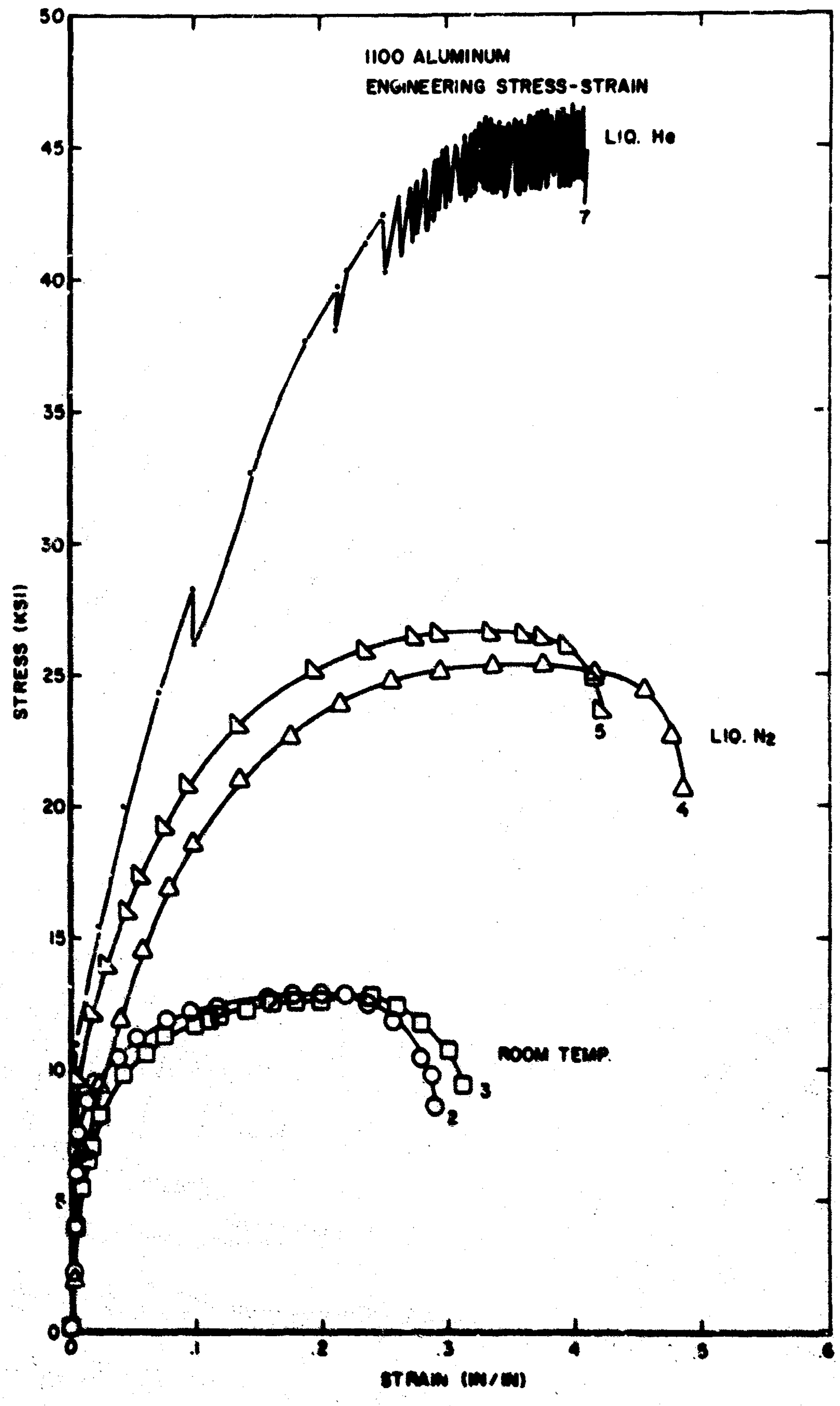

Figure 13. Engineering Stress-Strain 1100-0 Al

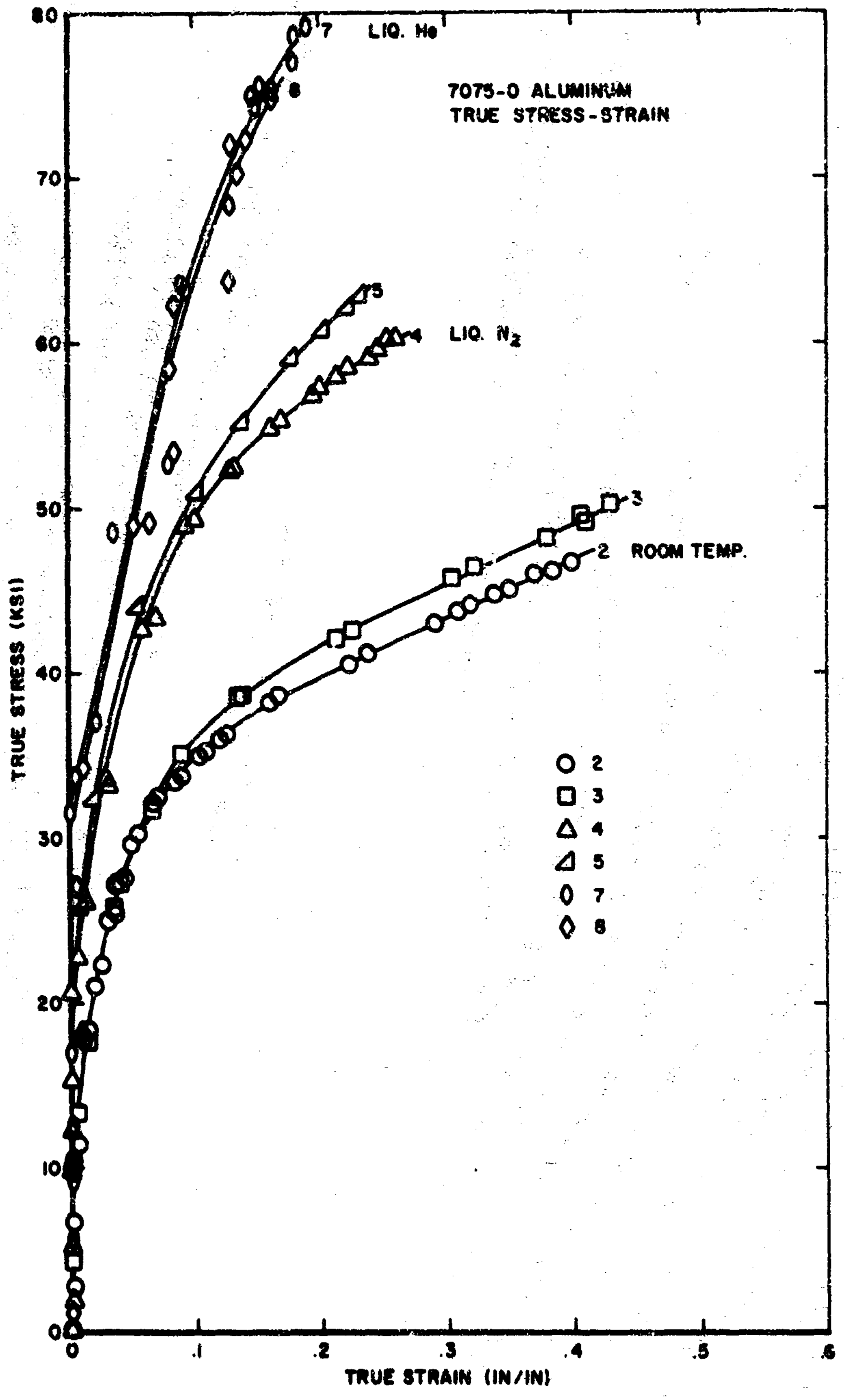

Figure 14. True Stress-Strain 7075-0 Al

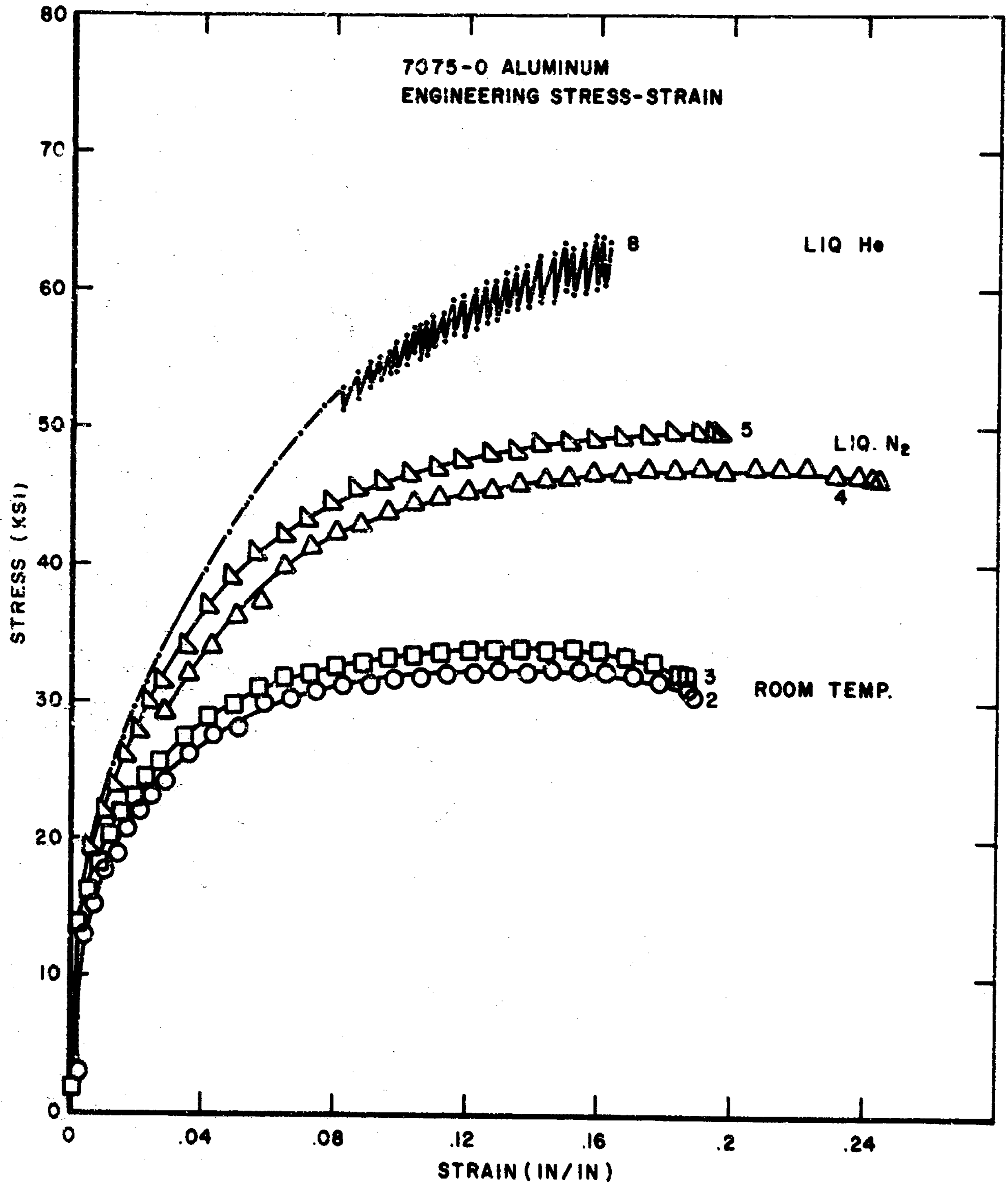

Figure 15. Engineering Stress-Strain 7075-0 Al

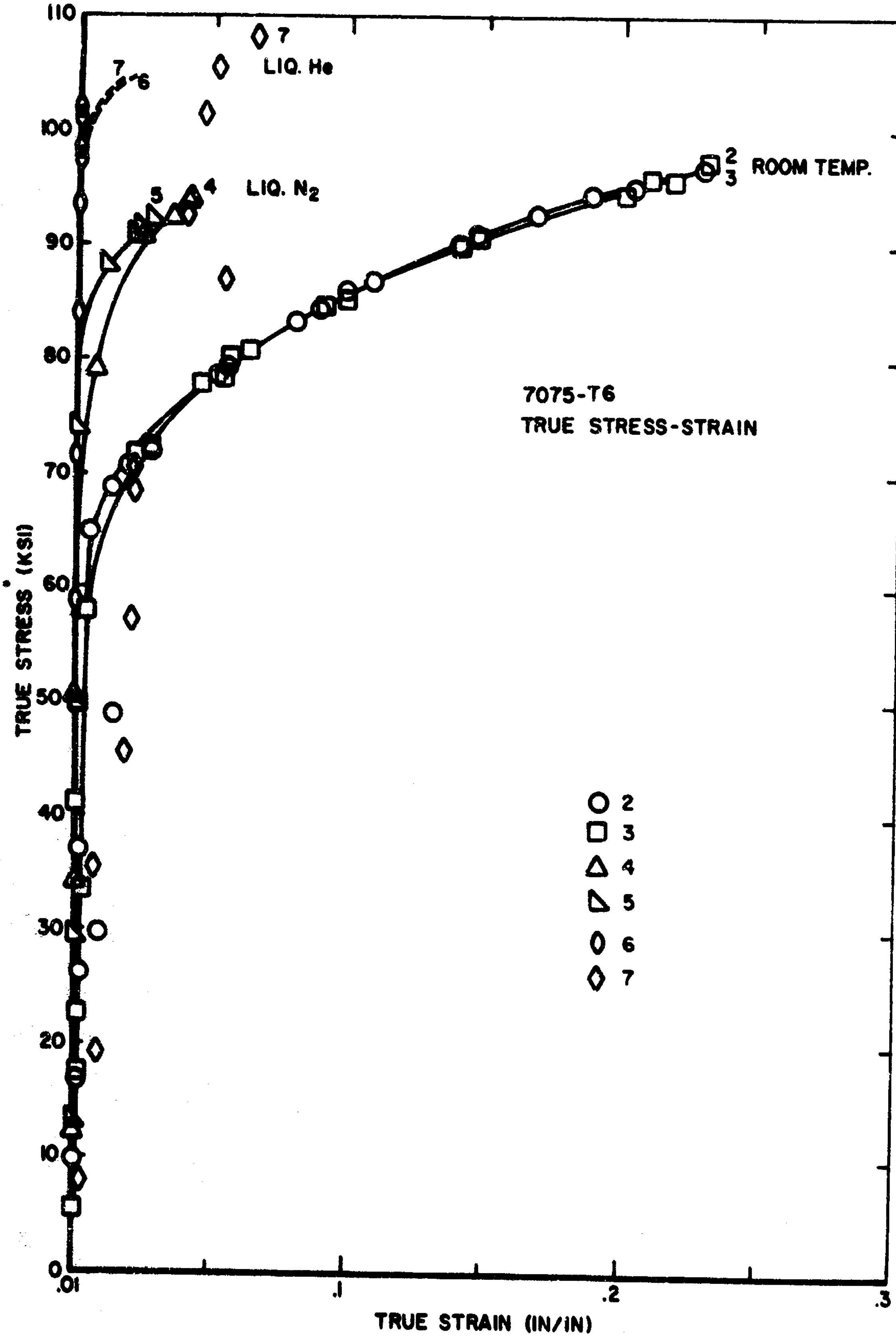

Figure 16. True Stress-Strain 7075-T6 Al

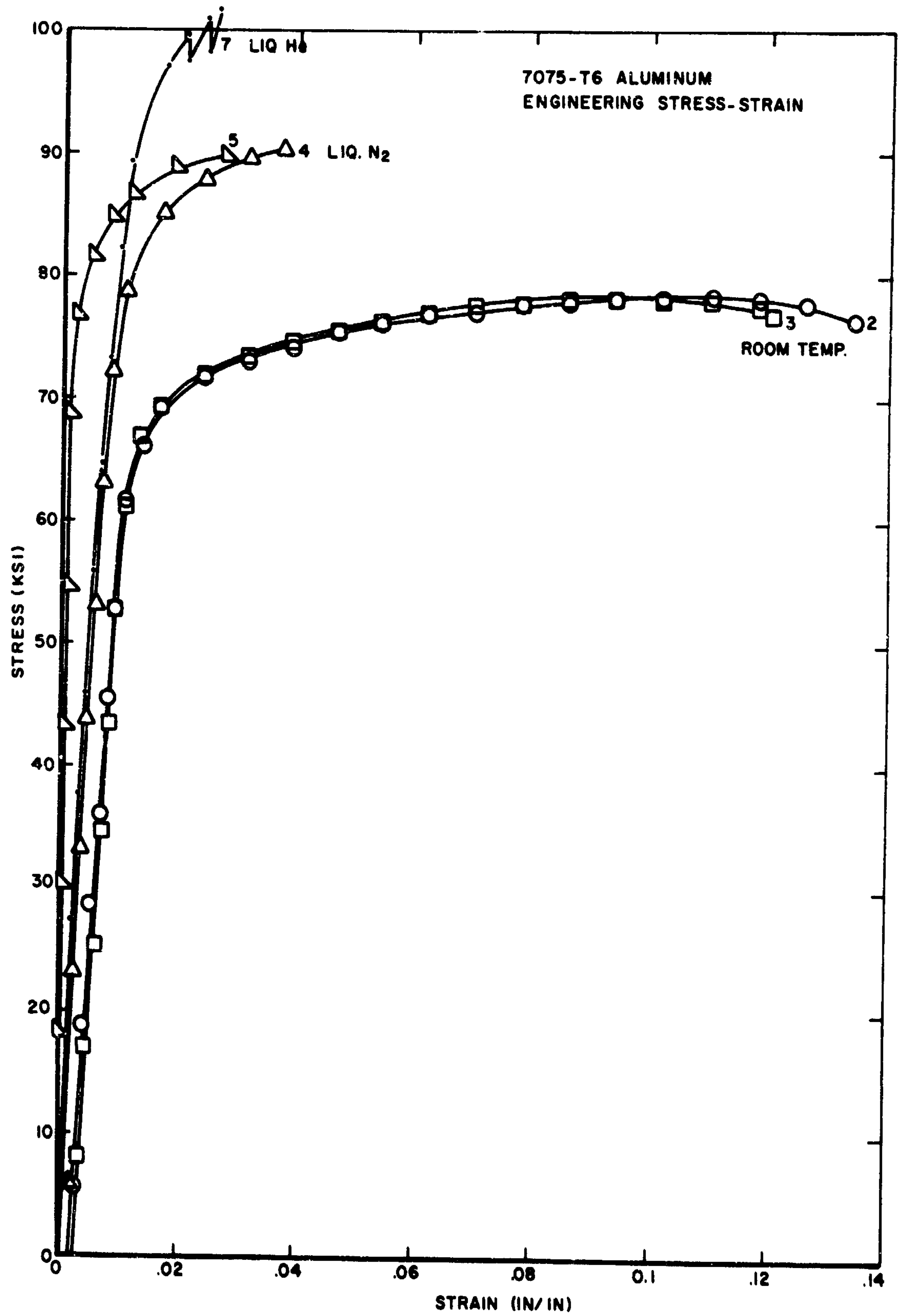

Figure 17. Engineering Stress-Strain 7075-T6 Al

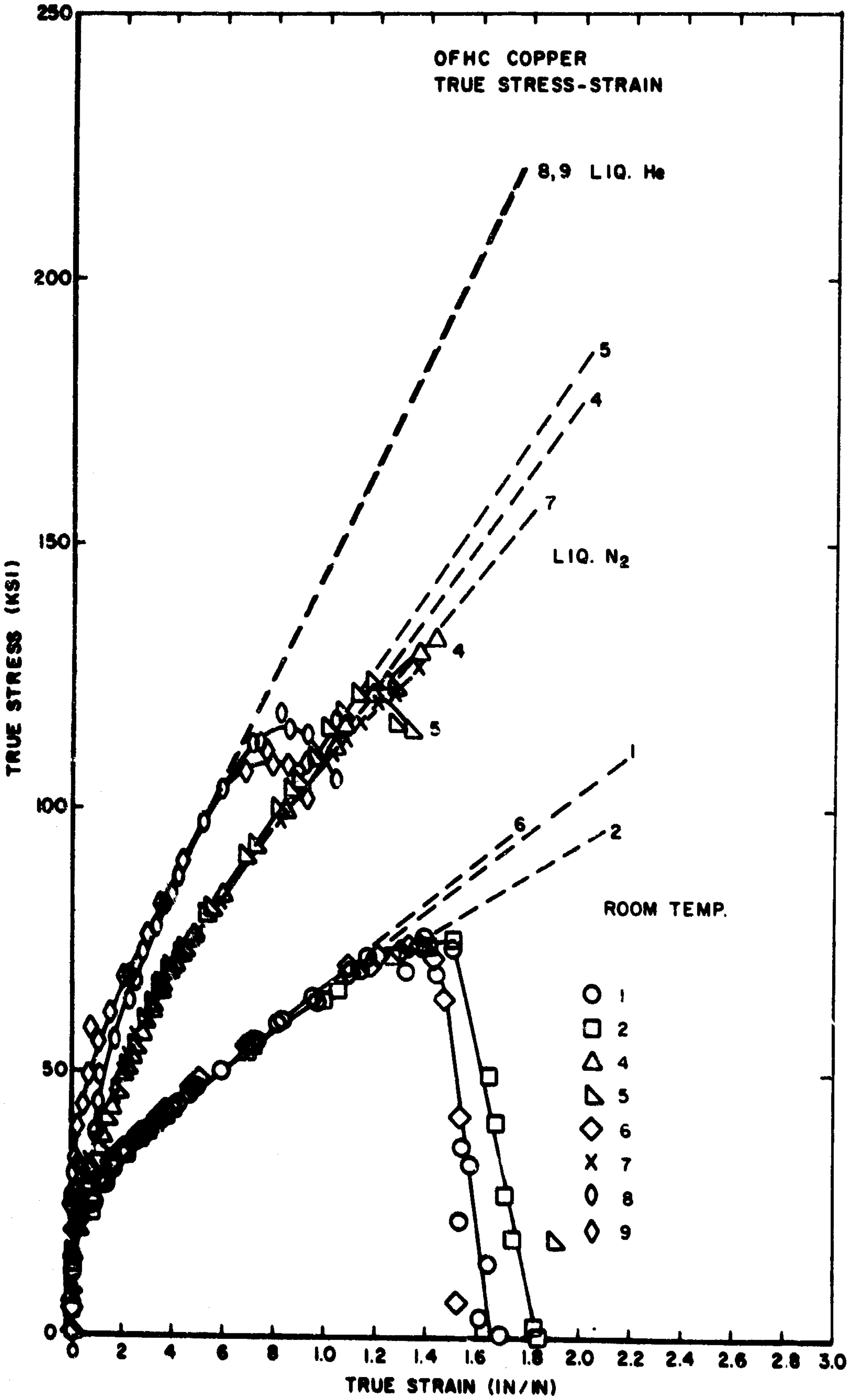

Figure 18. True Stress-Strain OFHC Cu

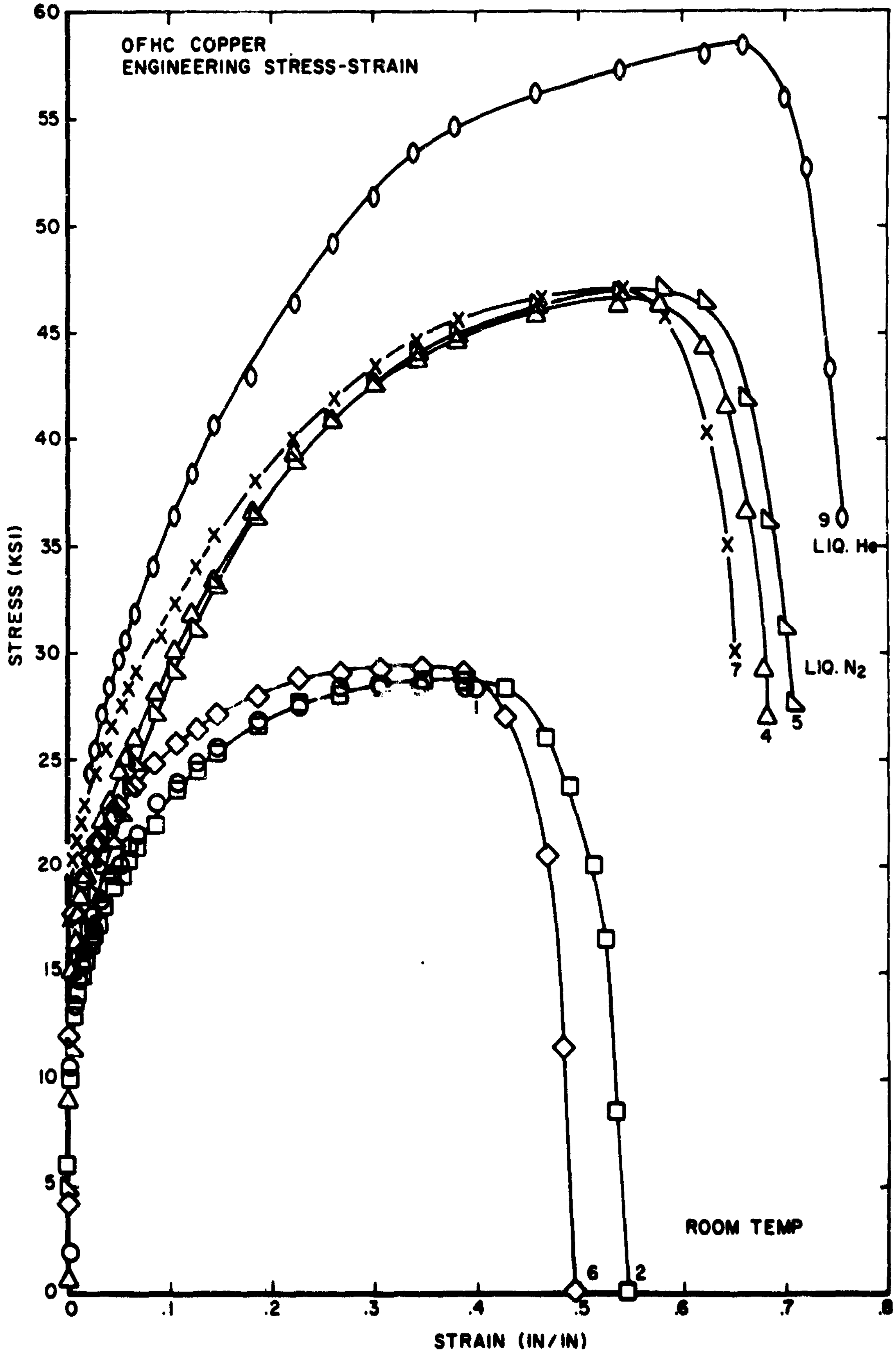

Figure 19. Engineering Stress-Strain OFHC Cu

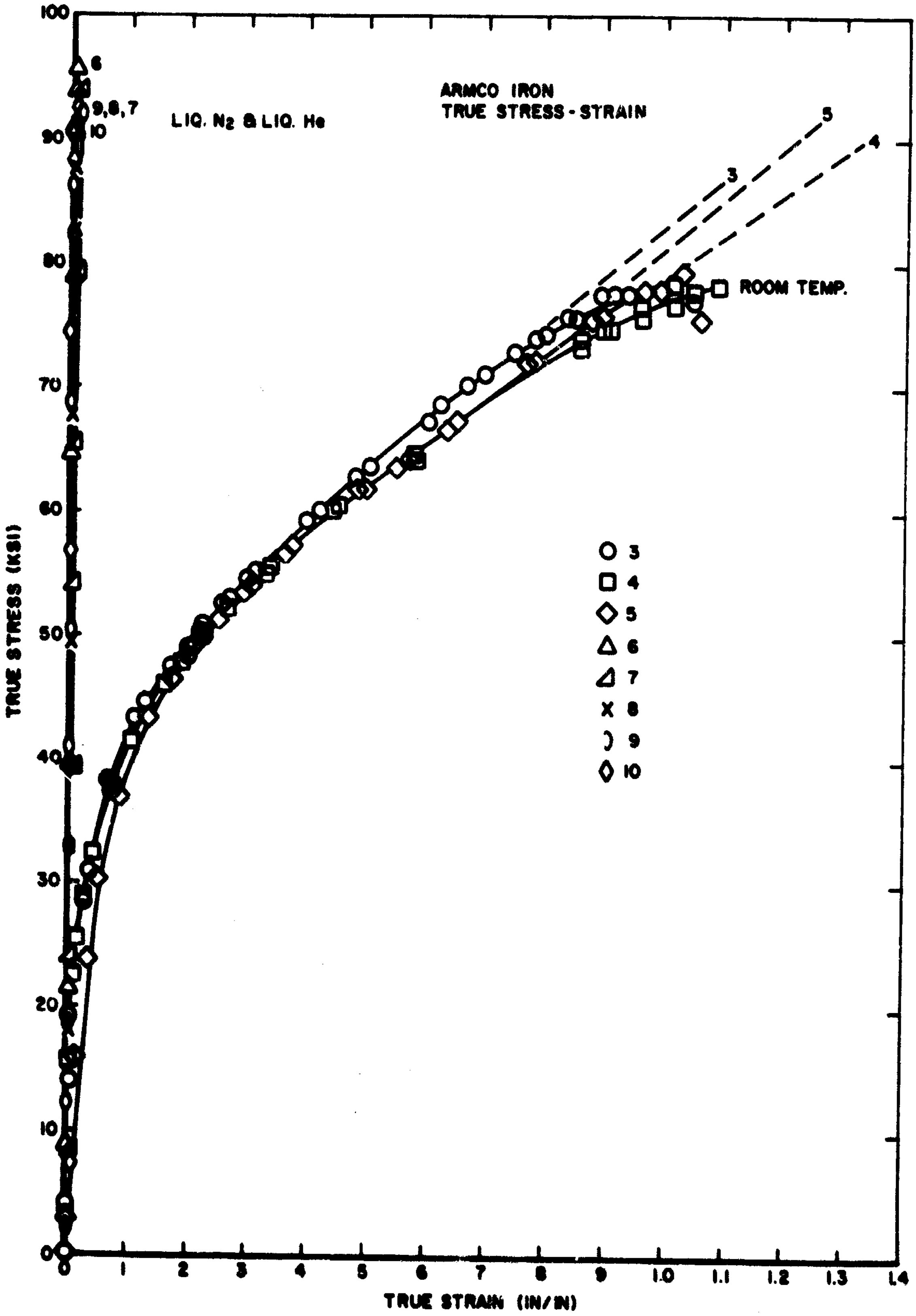

Figure 20. True Stress-Strain Armco Iron

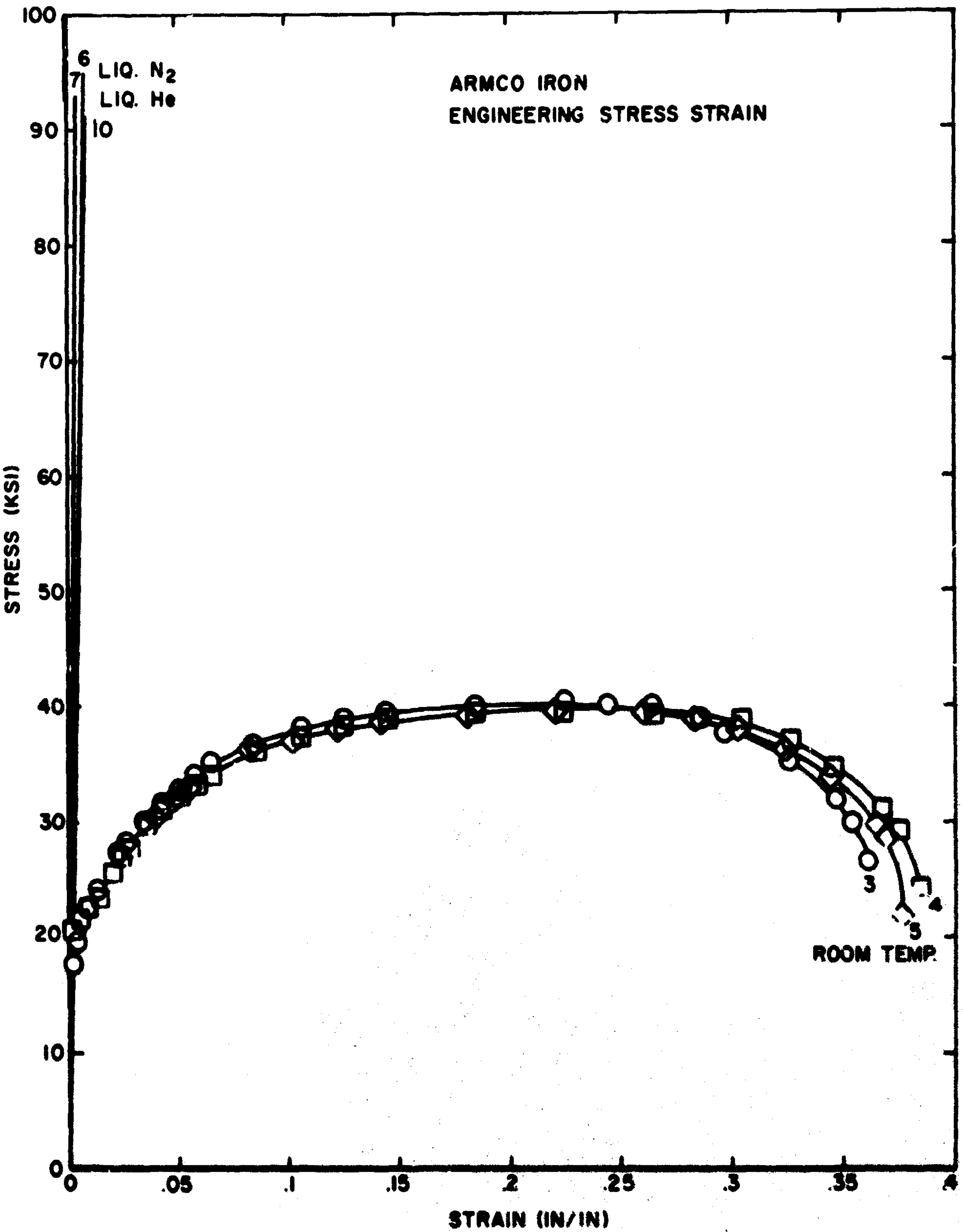

Figure 21. Engineering Stress-Strain Armco Iron

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13. ABSTRACT

The metallurgical and mechanical properties of several face centered cubic materials (1100 Al, 7075-0 Al, 7075-T6 Al, OFHC Cu) and a body centered cubic material (Armco iron) were examined. Prior to undergoing tensile testing the materials were insured to have a nonoriented equiaxed grain structure and underween chemical analysis and hardness tests. The materials were then tensile tested at 296°K in the atmosphere, at 77°K in a liquid nitrogen bath, and at 4°K in liquid helium. A continuous record of the axial load and of two perpendicular specimen profile traces produced a measurement of specimen true stress-true strain. Engineering stress-strain, elongation, and reduction in area were also calculated.

DD FORM 1 JAN 64 1473

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Stress Strain Tensile Tests Cryogenic Mechanical Properties Iron Copper Aluminum						

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